An American and European Technological Difference: The Early Motor Car Power Source

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ABSTRACT

Leslie Hannah contends that Europe was a more integrated market than the US at the turn of the twentieth century. This paper shows lesser integration is part of the explanation for why the US was slower than Europe to standardise technology on the internal combustion engine for the motor car. The remaining contribution is that of US abundant oil deposits and water that encouraged the American development of cheaper first cost steam engines. These used more (liquid) fuel and less capital. In Europe, oil fuel prices relative to skilled labour were less appropriate for steam and European car entrepreneurs therefore focussed on internal combustion engines. Distinctive US conditions were much less helpful for innovation and improvement before the continental US market was well established.

Keywords: technology choice- motor car – national advantage – market size and integration

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Despite extraordinary growth and productivity, the US economy in the early twentieth century was economically fragmented compared with the economies of western Europe[1]. Leslie Hannah has shown that European integration was achieved with ships and US integration with rail. Where Europeans used trains, the United States used horses. Coupled with the population distribution and the geography, transport mode differences created greater barriers to internal trade in the United States. Also, there was little competition in the US from outside, Hannah maintains; high tariff barriers protected the home market[2].

These features were major contributors to the temporary American interest in steam cars that European entrepreneurs generally avoided at the beginning of the twentieth century. Steam cars were light vehicles – often using bicycle components – and were powered by liquid fuel. For their success an essential innovation was the 'flash' boiler, where the tubes could be kept so hot that the water feed was quickly flashed into steam. The Stanley brothers' 1899 steam model boiler operated at pressures of about 150 psi, but was tested to 750 psi[3], and their car's range was about 60 miles with a maximum speed of around 25 mph[4].

In Europe the preferred car power source of the time was the internal combustion engine, burning similar fuel but in typically heavier vehicles. This paper contends that the technological divergence was because competition and knowledge diffusion in development of the motor car was more intense in Europe than in the US at the beginning of the twentieth century. Using data from motor trials and contemporary technical literature, it shows that rapid technological development in Europe eventually ensured that, even with US resource endowments – abundant oil and water - the internal combustion engine was a superior technology and that the US substantially switched to the European technological trajectory from 1902.

Some previous interpretations perhaps have been influenced by the widely supposed superiority of US industrial technology, later exemplified in the first half of the twentieth century by the world-dominating huge volumes of US motor cars produced at low prices[5]. In an industry subject to economies of scale some researchers have seen the earliest phase as the outcome of the same feature. A firm that happens to produce a good (internal combustion) car permanently gets ahead of rivals (steam cars) by bringing down product price as volume expands. Hence, in this view, the mere chance emergence of a product able to achieve temporary scale economies could lock in the adoption of internal combustion as the power source for the motor car for ever after. Yet other technologies (especially steam) supposedly could have performed as well[6]. Other writers instead have seen the victory of internal combustion as a technological inevitability, but without explaining the American lag behind Western Europe[7].

Examination of the technological history of the motor industry between 1894 and 1904 not only allows some testing of these views, but also sheds light on the drivers of technical progress at the beginning of the twentieth century. The following section describes the pattern of car power source use in 1900 in four countries The next section shows evidence for this initial international configuration being locally optimal choices of techniques. The third section explains how the technological trajectory illuminates the pace of internal combustion engine development relative to steam especially in the decade after 1894.

Power Source Innovation and Differences Between Countries

The early power source innovations were in Germany where Daimler's internal combustion engine of 1885 was fundamental. Daimler tested his engine on a motor boat in 1886[8]. In the same year Benz ran what is generally accepted as the first practical motor car[9]. Even though it was invented in Germany, the country was backward in using the internal combustion car. Understandably, in Mannheim, where Benz employed 800 men, there were quite a number of internal combustion engine motor cars on the streets[10]. But a total of only 24 private motor vehicles were registered in Berlin in 1900, showing how restricted Benz's home market was. Official German opinion regarded the railways as satisfactory transport, and therefore restricted road vehicles[11]. Moreover, steam road vehicles were subject to annual safety checks that were prohibitively expensive. In Mainz at the turn of the century the city council refused permission for a large company to run auto cabs and carriages for public conveyance[12].

By 1900 Benz had ceased to be the largest European and world internal combustion car manufacturer, making 600 cars (fewer than the French company Panhard et Levassor's output for instance)[13]. Nonetheless, Benz's production clearly dominated Olds' in the US; Olds made only 400 cars from mid-1899 through to 1900. Market repression by the German State did not depress European advances in the early motor industry because of the close integration of Western Europe[14].The centre of innovation moved to France, where product development flourished, helped by good roads and a buoyant export market to free trade Britain.

French competitive advantage may have been helped by legislation that did not preclude road testing of the infant motorcar, even though formally officialdom frowned upon road racing. The Prefect of Paris attempted to prevent the Paris-Amsterdam race but the organisers merely started the race earlier to avoid this prohibition[15]. As to the fine roads in the 1890s, these were a historical accident, due to the centralised French state and its perception of the need to control and defend[16].

The United States was exceptional where the power source for the early motor car is concerned, at the turn of the century. Measured by production volume in 1900, the internal combustion engine car was less popular than steam cars or even than electrically propelled vehicles (Table 1). The conclusion is broadly similar for car use; steam and electricity together powered more vehicles or models than internal combustion. In the 15 makes of cars most represented in New York registrations in early 1902, 438 were steamers, 320 were internal combustion cars and 104 were electric. The previous year in the New York car show 58 models were steamers, 23 were electric and 58 used the internal combustion engine[17]. Steam-powered traction engines were spreading rapidly in the United States as the century ended, having been widely employed as self-propelled power sources in Britain[18].

By 1904, the pattern and volume of US car output had been radically transformed; Table 1 shows the huge expansion of internal combustion cars while steam and electricity car output decline slightly, (though their growth resumed slightly in the next five years). The poor state of US roads - there were only 200 miles of paved roads outside cities - was a handicap for the US industry until cars became more powerful. But this should not have discriminated directly between power sources, though it may have inhibited the type of competition seen in France.

No production data comparable to those of the US are available for the European economies, but in Britain the composition of sales must have been very different from the US; in 1902 at least 9 in 10 of cars on British roads were estimated to be propelled by internal combustion engines[19]. Many of these were French. French car output was much greater than that of the US in 1900 despite

TABLE 1 ABOUT HERE

the enormous disparity in populations and incomes per head of the two countries[20] De Dion Bouton alone manufactured 1200 small internal combustion engine four wheeled cars in 1900, exceeding total US internal combustion output. Peugeot added perhaps another 500 internal combustion cars to the French total and Panhard et Levassor more than 700. By contrast the only prominent French steam car manufacturer, Serpollet, made around 100 cars compared with 1681 U.S. steamers[21].

Representation of foreign cars in rallies and races confirm the differing technologies and advantages of Western Europe, especially France, and the US. Free trade Britain provides a valuable market natural experiment. In the 1902 British Automobile Club Reliability Trial the only American cars competing were low priced steamers[22]. In the US Autoclub Trial of 1902 the French were prominent among the internal combustion engine models, but most of the US competitors were steamers[23]. Although the data are more problematic, this international pattern of power source use is corroborated by counts of models. The US dominated steam and electricity, while France and Germany focussed almost exclusively on the internal combustion engine[24]. The early UK industry was repressed first by safetly legislation and then by patents, leaving much of the national market to French imports[25].

The Choice of Technique

Why was US motor technology different from that of Europe in 1900? Market integration was one element favouring Europe, despite slower economic growth than the US and substantial national legal barriers. Close links of the common market of France, Germany and UK were exemplified by the travels of internal combustion innovator Daimler[26]. The openness and diversity of European legal and institutional environments prevented the repression of development opportunities everywhere even when, as in Germany, a national market was constrained by political disfavour.

The lesser market integration in 1897 is shown by the 'astonishing and unaccountable gap in the transmission of technical knowledge', both within the embryonic US industry and between the US and Europe[27]. Whereas the basic design of the motor car had been worked out in the 1890s in France by Panhard and Levassor, US engineers and designers continued to address into the twentieth century problems already solved in Europe[28]. This must be attributed to the market size, lack of market integration and competition compared with Europe (and therefore poorer information flows) and the 45% US protective tariff. The population of western Europe was more than double that of the US in 1900. Although average GDP per head was perhaps a quarter less than in the US the distribution of income was likely to have been more fundamental for the demand for cars.

Divergent market integration between the US and Western Europe is suggested by the number of competitors entered in the early motor trials. The Paris-Rouen trial of 1894 attracted 21 qualifying vehicles of which 17 finished. The next year the Chicago Trial – admittedly in worse weather – attracted only six vehicles of which two finished. The direction of the human capital flow is consistent with market integration conferring advantages on European motor industry development. US car-maker Winton hired as his chief engineer a French-trained Parisian working for Panhard and Levassor[29]. Other US firms also recruited French motor engineers at the turn of the century[30]. Henry Ford reverse engineered a crashed French car to find from what its valves were made. He then imported from Europe the vanadium steel technology[31].

Slow US car progress, in particular with the internal combustion engine, stemmed from the US focus on steam and electricity power, in turn attributable to factor prices. Natural resource abundance -water and oil - and skilled labour scarcity explain the early popularity of the steam car in the US; by the end of the nineteenth century the technology expensive skilled labour and used cheap water and distilled oil abundantly[32]. The US steam car employed a simpler engine than the internal combustion powered car, it could not stall, and needed no gear box. With the introduction of liquid fuel and the flash boiler, starting was nearly instantaneous providing that the pilot light was burning. Especially in hilly regions where soft water from horse troughs was available, the steamer's power and simplicity were much appreciated[33]. The very heavy consumption of water by, for example, US Locomobiles, was much less acceptable in Europe[34] This was not an intrinsic drawback of the steamer; when fitted with a condenser, as was the White steamer, the consumption of water was much reduced, but a condenser added to the first cost of the vehicle.

US Locomobile steamers in the British market of 1902 were cheap (£2-300) because they were simple. The vertical fire tube boiler was easy to make. Compared with the single cylinder internal combustion engine cars in the same price range, US steamers were also smooth running, thanks to their twin cylinders and not requiring a gear box. The steamer burnt gasoline (petrol) or kerosene (paraffin) like the internal combustion vehicle. Gasoline was usually preferred because it burned more cleanly and consistently. However, steamers were less physically efficient than internal combustion cars; the fuel was used to heat water which propelled the car whereas the internal combustion engine exploded the fuel to drive the piston directly[35]. As shown below, this typically meant the steamer burned twice as much fuel as the internal combustion engine car (at least in the US), and buyers in Britain took notice of this cost[36]. US gasoline prices were around 11-14 cents a gallon between 1899 and 1910 whereas in Europe they were perhaps three times higher[37]. By 1913, when US prices reached 17 cents, motorists in London and Paris were paying 50[38].

The heavy fuel consumption of the Locomobile, and the marked improvement of the White steamer, were amply demonstrated in the 100 miles non-stop USA Auto Club trial of May 1901[39]. For this sample steamers averaged 8.4 miles per gallon of fuel and internal combustion engine cars fuel efficiency was almost twice that, at 16.1 mpg.

Did running costs matter? As early as 1893 Levassor had sold cars to six doctors, five travelling salesmen and three insurance agents[40]. Such users may be expected to have compared the total costs of transport types for their businesses (the annual running costs of a horse were comparable to the purchase price). W E Buzby of New York in 1898 recounted one year of driving an electric Riker[41]. He covered 20 miles every day at a cost of $10 per month with 2 passengers in his $2500 carriage. Two years later Dr Zabriskie of Brooklyn, who drove a 6 inch cylinder Winton 25 miles a day, claimed to have saved $42 per month over horses, on unpaved roads and fuelled by stove gasoline at 13.5c per gallon[42]. The interest noted by 'practical capitalists' in the US 1895 race was further indication of commercial monitoring of the infant motor car[43].

Under some European conditions the greater fuel consumption of American steamers would offset their lower first costs. Certain expenses such as tyres were common to all motor vehicles. Survival of steam or internal combustion turned on the market assessment of the performance characteristics of the two power sources, having controlled for their generalised costs. As reliability, and therefore annual mileage and car life increased, fuel prices and fuel consumption assumed greater importance in full car costs. For low lifetime mileages, first costs dominated, but as mileages increased, the balance tipped against the fuel-intensive steamer. This could contribute a reason for the switch away from steam as the car developed.

The steam/ internal combustion engine running cost differential (RC) expression is;

$$RC= \Sigma^{n} \{(mpg_s^{-1}-mpg_{ic}-1)p.a\}/(1+r)^{n-1} \quad \ldots.(1)$$

where n is the number of years the car is kept on the road, mpgs, is the miles per gallon of the steamer, mpg_{ic} is the miles per gallon of the internal combustion engine car, p is the fuel price, a is the annual mileage and r is the discount rate. Using this expression Table 2 illustrates how in Europe higher fuel prices militated against steamers earlier than in the US. In the table the vehicle is assumed to be driven for 6000 miles a year[44]. Other assumptions are a European price of 35 cents a gallon, a five year life, and a discount rate of 5% p.a.

For one scenario the table uses the steam and internal combustion average fuel consumption from the US Trial of 1901 discussed above (internal combustion 16 and steam 8, miles per gallon). Then, the present value of differential running costs in Europe was more than £100 (Table 2). But this is probably an overstatement because with cheaper fuel in the US, internal combustion cars and steamers were likely to consume more fuel with bigger engines. In the British Trial of 1902 steamers averaged about 16 miles per gallon of petrol and internal combustion cars. At a European fuel price level the fuel-consumption cost penalty of steamers was nearer £40. The US cost penalty of steamers can be found, when US fuel prices were one third those in Europe, by dividing the European cost penalty by three. This small figure offered a minimal incentive to ignore the merits of steamers. Doubling the expected mileage doubles the cost penalty. Comparing European (free trade) price differentials of, say, Locomobiles at £200 and single cylinder internal combustion

Renaults or De Dion Boutons at £245 in 1902 it looks possible that the extra Locomobile fuel cost could be the explanation.

TABLE 2 ABOUT HERE

These calculations are supported by the market valuation of US steamers' fuel consumption in the UK according to a hedonic price index estimated for 42 vehicles that finished in the 1902 Automobile Club UK 650 mile trial[45]. In a competitive market for a differentiated product such as a car, the price will be higher if it supplies more characteristics that some buyers want. The way attributes, such as horsepower, number of cylinders and fuel consumption, are combined and how much they cost depend upon the technology embodied in the car model. Those models employing superior technology will either supply more desired characteristics for the same price than rivals, or the same attributes as competitors but at a lower price. Either way, there should be a frontier of best practice technology marked out by superior car models. Behind the frontier less successful car technologies should be spread at greater distances the less effective are the models. The less integrated the market, the greater the dispersion behind the frontier and the further from the frontier is a model, the smaller the market share it is likely to achieve.

If fuel consumption mattered to British buyers in 1902, as the hypothesis about the development of internal combustion engines requires, then 'thirsty' vehicles would only be demanded at lower prices, other things being equal. If steamers were inconvenient in some way relative to internal combustion cars then again, other things being equal they would be sold at a discount.

Price can be thought of as a cost that the market is willing to pay, and therefore as a valuation of the car's characteristics. The formulation adopted here is a stochastic frontier cost equation of the form

$$\text{Price} = a_0 + a_1 \text{ Fuel} + a_2 \text{ Cylinders} + a_3 \text{ Horsepower} + v + u. \qquad \ldots (2)$$

v is the normally distributed disturbance term and u is the 'technical efficiency' component, with a one-sided distribution[46]. The density function of $v + u$ is asymmetrically distributed about zero. In (2) and Table 3 $u \geq 0$ is assumed to be from a half-normal distribution and the frontier functions are estimated by maximum likelihood. The closer a car price is to the lowest on the market for the combination of characteristics embodied in it, the smaller is u[47]. The other model reported in Table3 simply replaces u with a dummy variable for steam cars and is estimated by OLS.

The variance (σ^2=sig2) of inefficiency (measured by *u*) is statistically significant in equations (i) and (ii) of Table 3 and for equations (iii) and (iv) the explained variance is high at over 90 percent[48]. The efficiency terms for each car show that US steamers were generally no worse than the average Trial entrant (although one Locomobile was the fifth most inefficient, another was the fourth most efficient). In 1902 US steamers were a competitive technology in the UK free trade market; their qualities took them so close to the UK efficiency frontier that even with different factor prices in the UK their high fuel consumption was offset by their lower price.

The biggest inefficiency terms were for an internal combustion engine Panhard – that received the highest marks in the 1902 Trial[49] - and for two expensive (£600) French steamers, the Gardner-Serpollets (the only European steamers completing the Trial). These conclusions about the efficiency terms are checked in OLS equations (iii and iv) with dummy variables. The equation confirms that the US steamers were, on average, judged no different from other cars once their higher fuel consumption was taken into account and that the French Serpollets were unusually expensive. Serpollet's cars were not a commercial proposition [50].

These equations also show that vehicles with a high fuel consumption, in relation to their weight and otherwise, were priced at a substantial discount. According to equation (i) this greater fuel consumption would reduce by 17% the price for which these cars could be sold (and the probably more reliable OLS equation (iii) by 20%). The mean fuel consumption for all steam cars was 46 gallons,[51] statistically highly different from the 30 gallon average for internal combustion. From the OLS coefficient of (iv) this implies a 16% lower price for steamers. Overall these results indicate that a £200 Locomobile would have been competitive with an internal combustion car in the UK, such as the single cylinder Renault, priced at £245, and above.

TABLE 3 ABOUT HERE

They are also consistent with (the third row of) Table 2. Other implications of the regression are that an increase in the number of cylinders from, say, two to four would raise the price by about (2 x 0.19=) 38%. A car of 12 horsepower, say, would on average, compared with a 6 HP car, fetch a price around (6 x 0.04 =) 24% higher.

Although US steamers were so close to the frontier in the US that they could compete in the different economic environment of the UK in 1902[52], the trajectory of power source development ensured this competitiveness could not be maintained. By 1903 US internal combustion engine cars (Winton, Cadillac and Oldsmobile) were entering and completing the RAC trial in the UK (joining US steamers Stanley and White); the switch in technological trajectory was underway[53].

The Internal Combustion Engine Trajectory and Steam 'Lock out'

High US labour productivity in manufacturing is often linked with distinctively American 'technological trajectories'[54]. Some technologies have more progressive trajectories, potential for productivity improvement, than others at given stages of development. Trajectories are determined by physical laws, national resources and institutions as well as by parallel developments in other technological fields[55]. Though initially, standardised US demand, raw material abundance and skilled labour scarcity merely directed entrepreneurs to choose techniques different from those in Europe, the competitive success of. US multinational enterprise abroad suggests that American technologies were typically more productive in non-American environments as well[56]. As US production experience accumulated in specific technologies, the incentives for business in other economies to adopt US techniques became greater.

If this was the universal pattern of innovation at the turn of the century, the early and enthusiastic US adoption of the steam car might imply the technology would eventually spread to the rest of the world. But quite quickly the opposite occurred. Either historical accident 'locked out' US steam technology or US resource endowments did not invariably direct the market to adopt the most progressive technological trajectories

There are three prominent pieces of evidence that steam cars were not locked out by internal combustion cars. The first is that the choice of propulsion technique emerged in repeated open competition in the European market. A temporary advantage in this competition would not be enough for a permanent lead unless volume production substantially reduced unit costs of a successful (internal combustion) car model (the Ford Model T is sometimes cited) that then ‘locks out’ other technologies. If the largest volume producer got to stay ahead then the Locomobile steamer should have continued to flourish; in the US , unlike Europe, the earliest high volume model was the Locomobile steamer (a total of 5200 were sold between 1899 and 1903). But this did not prevent the internal combustion Oldsmobile in 1902 exceeding the peak annual production achieved by Locomobile (selling 2500, then 4000 in 1903 and 5000 in 1904[57]) Internal economies of scale were not a plausible source of ‘lock in’ in this period.

The second piece of evidence that steam cars were not locked out is that, although by 1904 Oldsmobile may have been the largest producers, other internal combustion car companies produced over 70% of US internal combustion output. External rather than internal economies would need to be drivers of permanent advantage. When Olds moved to a new site in 1901 much of the manufacturing was contracted out to three firms respectively to make engines, transmissions and bodies. But many of car components benefiting from scale economies of interchangeable parts mass produced would have been common to both steam and internal combustion cars[58]. Earlier, the Stanley brothers had demonstrated the general principle by utilising bicycle manufacturers to supply the frame for their steam cars[59].

The availability of component manufacturers is an external economy that might have locked in an inferior technology. But the wide spatial distribution of US car manufacturing in 1900 suggests that there were no major external economies in production. Massachusetts with 17 establishments produced the largest number of cars, Connecticut with four establishments made the highest value cars, with New York achieving third place according to both criteria and first place with number of establishments, 21[60]. Spatial concentration increased by 1904 moving away from these areas, as internal combustion car production took off. As earlier with traction engines, the mid-West was by then the locational focus, suggesting that there were fundamental forces at work other than production external effects . Michigan and Ohio dominated internal combustion engine car production, and therefore all US car production, as much as they had with traction engines four years earlier (49.5%). The internal combustion engine by then better satisfied the demand from agriculture, displacing steam traction engines. The triumph of internal combustion therefore was not an accident due to the temporary achievement of one model or manufacturer. Good models were a necessary condition for volume production, not vice versa. The ‘lock in’ hypothesis gets matters the wrong way round.

The third piece of evidence is that established producers and new entrants tried steam and found it less viable than internal combustion power for cars. Olds and Ford among others in the US[61] and De Dion in France experimented with steam before switching to internal combustion, and Locomobile abandoned steam power in 1904, also counts against the notion that ultimately steam was a viable competitor for cars. Before Ford moved into high volume production steam had been virtually eliminated.

Although Comte Albert de Dion and George Bouton won the 1894 Paris-Rouen trial in a steamer, in the following year's Paris-Bordeaux trial De Dion’s steamers did not finish. This failure confirmed De Dion’s belief in the superiority of the internal combustion engine for cars, on which he focused. The result was the De Dion-Bouton internal combustion engine of 1895 that could achieve 1500 rpm, double that of the Daimler engine, also with a far superior power to weight ratio[62]. Before Daimler’s engine, oil and gas engines achieved only about 1 hp for every 300 lbs of engine weight. Daimler improved this to 1 hp for 90 lb. The De Dion Bouton engine of 1895 managed one horsepower for about every 25 lbs up to 8 hp (improvement by a factor of 12)[63]. As well as those in De Dion-Bouton tricycles and cars, many De-Dion internal combustion engines were sold separately and abroad, as the 1898 Paris exhibition showed; half the ninety exhibitors at the exhibition used De Dion engines[64].

As the De Dion case shows, the European internal combustion car technical trajectory is particularly amenable to study because the series of public trials created performance data for the public domain[65]. In France, the series of car races or rallies beginning in 1894 (Paris-Rouen) ultimately secured the triumph of internal combustion engines, and also displayed the erratic performance of steam power. Thereafter only two steam vehicles completed their courses, the first as the slowest in 1895, the second as the fastest in 1897. Despite this last success, the decision of the technological selection process was conveyed by so few steamers finishing. De Dion Bouton, the largest French motor manufacturer in 1900 measured by employment, whose owner drove the successful steamer in 1897 race, abandoned steam for cars soon after[66].

Each trial indicates a different point on the technological trajectory of the French internal combustion engine as a power source for the motor car. The rise in average, maximum and minimum speeds over the years 1895 to 1900 is a fair indication of the rapid improvement in the effective power output, and reliability, of the internal combustion engine (Table 4). Each year's observation may not be exactly comparable with the next, because the distance travelled differs. But maximum and average speed rise rapidly and inexorably.

TABLE 4 ABOUT HERE

Unfortunately, there is only indirect and piecemeal evidence of the technical trajectory of steam cars - such as world speed records. The Frenchman Leon Serpollet patented a 'flash' boiler in 1887 and continued to work on improving his steam cars, culminating in his world speed record of 75 mph in 1902[67]. But he sold very few of these luxury products. The emergence of the most successful steam car design in the US, the Stanley's Locomobile, illustrates the contribution of localised learning and the transmission of implicit knowledge through personal contact and proximity. It also suggests a narrower range of competition and information exchange than in Western Europe. The Stanley brothers, the most successful US steam car makers drew on a local inventive tradition when they entered the new industry from photography, their first success. Sylvester Roper (1824-1896) of Roxbury Massachusetts, spent much of his life experimenting with road steamers. George E Whitney worked in Roper's shop occasionally and finished his first steamer, much like Roper's vehicles, in the year Roper died. The Stanley brothers near the same town as Whitniey, Boston, made two steamers in 1897 and 1898 rather similar to those of Whitney but lighter. These were prototypes for the best-selling Locomobile[68]. The brothers went on to build the Stanley steamer that recovered the speed record in 1906, achieving 121mph . But by then it was clear the era of steam cars was over in the Us as well as in Europe; convenience and reliability were more important for the market than a high top speed.

Concluding Remarks

Leslie Hannah's insight in to US market integration around 1900 has been employed here to explain a surprising if temporary divergence between European and American technologies; the survival of the steam car in the US after it had been largely abandoned in Europe. The paper adds a second explanation for the US technological lag; evidence that these steamers were examples of natural resource-intensive technology likely to be too expensive for Europe. Liquid fuel was far cheaper in the US and could be consumed more lavishly, as the steam car required. The early US steam car was made at a lower first cost than the more complex internal combustion engine vehicle and, for a brief while, that promised to offset the higher fuel costs. In this instance, unusually however, US technology was not superior to that in Europe.

The US switched technologies or techniques when it did for the same reason Europe changed earlier- the internal combustion trajectory was more progressive than steam and running costs became more important as the lifetime mileage of a vehicle increased. Europe adopted the winning technology in this case because competition and a wider more integrated market showed that the natural resource-economising technology happened to yield greater benefits in the long term. The eventual similar outcome on the two continents suggests the internal combustion engine filled a distinct ‘ecological niche’.

Even within Europe, institutional environments and national traditions were sufficiently varied to recognise experimentation within the major economies as different realisations of similar innovative processes. Over the longer run, the emergence of the internal combustion engine motor car was not, as sometimes maintained, sensitive to ‘chance’, such as the availability of good roads or repressive legislation. Economies of scale were no source of 'lock in' to internal combustion engines, for long before Fordism took root, the selection process was complete.

Nor was the (1895) Selden patent, requiring all US automobile manufacturers to pay royalties, an alternative explanation for US internal combustion backwardness[69]. The small size of the surcharge and the ease of access to the patent right ensured that. The Lawson patent probably mattered more for the retarded production of UK internal combustion (working at Wolseley, Austin abandoned an early car design because of it[70]) but the surcharge possibility was removed in 1901. And anyway, the numerous French car imports to the UK were internal combustion, and dominated usage.

Similar circumstances triggered other successful innovative responses in Europe towards the end of the nineteenth and beginning of the twentieth centuries. The variety of jurisdictions within the integrated European market allowed Marconi to take his wireless telegraphy expertise from Italy where it was rejected, to Britain in 1896, where it was developed[71]. From there spinoff organisations included the Radio Corporation of America[72]. Innovative products substituted for scarcer natural materials. The Mannheim company BASF in 1897 launched its synthetic version of the most important natural dye, indigo, and then the company began developing the Haber-Bosch process to synthesise ammonia from 1902[73]. The UK company Courtauld's innovation of Rayon in 1904/5 was an alternative to silk, spawning a US subsidiary in 1910[74]. The Belgian Ernest Solvay developed the ammonia-soda process to provide alkali for the soap, textile, and glass industries. In 1884 the Solvay brothers licensed production of 'soda ash' in the US, and formed a joint venture to build and operate a plant in New York. By the 1890s, Solvay process plants produced most of the world's 'soda ash'[75].

Successful innovation does not require the same conditions as high productivity manufacturing production, at which clearly the US excelled[76]. Fast US market growth allowed the development of, and investment in, established machinery (as in continuous paper production[77]). Nonetheless the US could (temporarily) lag Europe in what were to become major technologies. Distinctive US conditions were much less helpful for innovation and improvement, before the continental market was well established.

Bibliography

Abelshauser, W, von Hippel W, Johnson J A and Stokes R G. *German Industry and Global Enterprise: BASF: The History of a Company.* Cambridge: Cambridge University Press, 2003.

Aigner, D., Lovell, C.A. K. and Schmidt, P. 'Formulation and Estimation of Stochastic Frontier Production Function Models'. *Journal of Econometrics* 6 (1977) 21-37.

Arthur W B 'Competing Technologies, Increasing Returns and Lock-in by Historical Events' *Economic Journal* 99 (1989) 116-131

Autocar (various)

Baker, W. J., *A History of the Marconi Company.* London: Methuen, 1970.

Barjot, D., 'Advances in Road Construction Technology in France' in T C Barker ed. *The Economic and Social Effects of the Spread of Motor Vehicles.* London: Macmillan, 1987.

Barker, T. C. ‘Introduction’ in T C Barker ed. *The Economic and Social Effects of the Spread of Motor Vehicles*. London: Macmillan, 1987.

Beasley, D. *The Suppression of the Automobile - Skulduggery at the Crossroads.* New York: Greenwood. 1988.

Bertram, K, N Coupain, E Homburg and G Kurgan-van- Hentenryk, *Solvay, History of a Family Multinational Firm,* Cambridge: Cambridge University Press, 2013.

Broadberry, S. 'Technological Leadership and Productivity Leadership in Manufacturing since the Industrial Revolution: Implications for the Convergence Debate.' *Economic Journal,* 104 (1994): 291-302.

Broadberry, S. N. *The Productivity Race: British Manufacturing in International Perspective 1850-1990.* Cambridge: Cambridge University Press, 1997.

Caunter, C. F., *The Light Car*, Science Museum, HMSO, 1970.

Coleman, D. C., *Courtaulds: an Economic and Social History, vol. 2, Rayon.* Oxford: Clarendon, 1969.

Cummins, C. L. jr. *Internal Fire.* Oregon: Carnot Press, 1976.

Davison, C. St C. B., *History of Steam Road Vehicles Mainly for Passenger Transport.* London: Science Museum, 1953.

Diesel, E. , Goldbeck, G. and Schildenberger, F. *From Engines to Autos: Five Pioneers in Engine Development and Their Contributions to the Automotive Industry*, Chicago: Henry Regnery, 1960.

Dosi, G. *Technical Change and Industrial Transformation*. London: Macmillan, 1984.

Flink, J. J. *America Adopts the Automobile 1895-1910.* Cambridge Ma.: MIT Press, 1970.

Ford, H. *My Life and Work.* London: Heinemann, 1923.

Foreman-Peck, J. S. ‘The American Challenge of the Twenties U S Multinationals and the European Motor Industry.’ *Journal of Economic History,* 42 (1982) 865-881.

Foreman-Peck, J. S. ‘The Path Dependence of Technological Trajectories: The Battery Electric Vehicle,’ in L. Tissot and B. Veyrassat eds. *Technological Trajectories, Markets, Institutions. Industrialized Countries 19th-20th Centuries.* Bern: Peter Lang, 2002.

Hannah, L., 'Marshall's 'Trees' and the Global 'Forest': Were Giant Redwoods Different?' in Lamoreaux N., Raff D. and Temin, P. eds., *Learning by doing in Markets, Firms, and Countries*. Chicago: University of Chicago Press, 1999.

Hannah, L., 'Logistics, Market Size and Giant Plants in the Early Twentieth Century: A Global View.'*Journal of Economic History*, 68(1) (2008) 46-79.

Hannah, L., 'Trust, Reputation and Regulation: Securities Markets in Europe, the USA, and Japan Before 1914' in Pettigrew, W. A. and Smith, D. C., eds. *A History of Socially Responsible Business, c.1600–1950,* Springer, 2017.

Hasluck, P. N. ed., *The Automobile: A Practical Treatise on the Construction of Modern Motor Cars.* London: Cassell, 1902 and 1906.

Jenkins, R., *Motor Cars and the Application of Mechanical Power to Road Vehicles*. London: Fisher Unwin, 1902.

Laux, J. M., 'Diesel Trucks and Buses: Their Gradual Spread in the United States' in T. C. Barker ed. *The Economic and Social Effects of the Spread of Motor Vehicles*, London:Macmillan, 1987.

Laux, J. M. 'Steam Cars' in G.S. May ed. *The Encyclopaedia of American Business History and Biography: The Automobile Industry 1896-1920.* New York: Facts on File, 1990.

Laux, J. M., *The European Automobile Industry.* New York: Twayne Publishers,1992.

Laux, J. M. and L. J. A. Villalon, 'Steaming through New England with the Locomobile.' *Journal of Transport History* 2nd series 5:2 (1979) 65-72.

Liebowitz, S. J. and Margolis, S. E., 'Network Externality: An Uncommon Tragedy.' *Journal of Economic Perspectives,* 8 (1994) 133-150.

Lloyd Jones, R. and Lewis, M. J., 'Technological Pathways, Modes of Development and the British National Innovation System' in L. Tissot and B. Veyrassat eds. *Technological Trajectories, Markets, Institutions. Industrialized Countries 19th-20th Centuries.* Bern: Peter Lang, 2002.

Magee, G., 'Technological Divergence in a Continuous Flow Production Industry: American and British Paper Making in the Late Victorian and Edwardian era.' *Business History* 39:1 (1997) 21-46.

McLaughlin, C. C. 'The Stanley Steamer: A Study in Unsuccessful Innovation' *Explorations in Entrepreneurial History* 7:1 (1954) 37-

McShane, C., *Down the Asphalt Path: The Automobile in the American City*. New York: Columbia University Press, 1994.

Merki, C. M., 'The Birth of Motoring out of Sport' in L. Tissot and B. Veyrassat eds. *Technological Trajectories, Markets, Institutions. Industrialized Countries 19th-20th Centuries*. Bern: Peter Lang, 2002.

Meeusen, W. and van den Broeck, J., 'Efficiency Estimation from Cobb-Douglas Production Functions With Composed Error.' *International Economic Review* 18, (1977) 435-444.

Mokyr, J. *The Lever of Riches: Technical Creativity and Economic Progress*, Oxford: Oxford University Press, 1990.

Nelson, R. R. and Wright, G., 'American Technological Leadership' *Journal of Economic Literature* 30 (1992)1931-64.

Noble, D. and G. Mackenzie Junner, *Vital to the Life of the Nation: A Historical Survey of the Progress of the British Motor Industry from 1896 to 1946*, London: Society of Motor Manufacturers and Traders, 1946.

Rae, J. B. 'The Electric Vehicle Company: A Monopoly That Missed.' *Business History Review,* 29:4 (1955) 298-311.

Rae, J. B., *American Automobile Manufacturers: The First Forty Years*, Philadelphia and New York: Chilton , 1959.

Rae, J. B., *The American Automobile Industry*. Boston Mass.: G K Hall, 1984.

Raff, D. M. G. and Trajtenberg, M. 'Quality Adjusted Prices for the American Automobile Industry 1906-1940' in T. F. Bresnahan and R. J. Gordon, eds. *The Economics of New Goods*, Chicago: National Bureau of Economic Research, 1996.

Saul, S. B., 'The British Motor Industry to 1914.' *Business History*. 5:1 (1962) 22-44.

Siebertz, P., *Gottleib Daimler,* Stuttgart: Reclam Verlag, 1950.

United States, *Twelfth Census 1900, Manufactures* vol X , Washington: US Census Office, 1902.

United States Special Consular Report, *Vehicle Industry in Europe* Doc no 741 56th Congress 1st session House of Representatives, Washington: GPO, 1900.

Williamson, H. F., R. L. Andreano, A. R. Daum and G. C. Klose, *The American Petroleum Industry:The Age of Energy 1899-1959.* Westport Connecticut: Greenwood Press, 1981. Original edition Northwestern University Press 1963.

Worby Beaumont, W., *Motor Vehicles and Motors: Their Design Construction and Working by Steam, Oil and Electricity.* London: Constable. 2 vols 1900, 1906.

Wright, G., 'The Origins of American Industrial Success 1879-1940.' *American Economic Review,* 80 (1990) 651-668.

Yergin, D., *The Prize: The Epic Quest for Oil, Money and Power*, New York: Simon & Schuster, 1991.

Appendix. Car model distance from UK least price frontier 1902.

(Most 'inefficient' highest value)

	u Tech. effic. Eqn (1) Table 3	
Panhard	0.50693781	1
Gardner-Serpollet	0.50322476	2
Gardner Serpollet	0.43299542	3
Germain	0.38850413	4
Locomobile	0.3485114	5
Daimler	0.3036191	6
MMC	0.30084389	7
Daimler	0.28835662	8
Maudslay	0.28283319	9
Ariel	0.27947913	10
Decanville	0.27913832	11
Locomobile	0.27066971	12
De Dion Bouton	0.26594129	13
Daimler	0.26259436	14
Gladeator	0.20032741	15
James-Browne	0.1966072	16
Wolseley	0.19226487	17
Humber	0.19023353	18
Pascal	0.18107638	19
Simms	0.15731874	20
Renault	0.14424315	21
White steamer	0.13566323	22
MMC	0.13531233	23
Clement	0.12574076	24
Pascal	0.12138306	25
Wolseley	0.11889155	26
Peugeot	0.11792734	27
Germain	0.11746051	28
White steamer	0.11704075	29
Century	0.1020298	30
Belsize	0.09229987	31
De Dion Bouton	0.08876098	32
Brush	0.0758044	33

MMC Voiturette	0.07541759	34
Locomobile	0.06661063	35
Star	0.06545856	36
Clement	0.06264601	37
New Orlean	0.06018127	38
Locomobile	0.05906994	39
Brooke	0.05289157	40
Wolseley	0.03585877	41
Gladiator	0.03521615	42

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Notes

1. Hannah, "Logistics, Market Size and Giant Plants".
2. Hannah, "Marshall's Trees and the Global Forest".
3. Not consistent with Rae's claim (Rae *American Automobile Industry,* 19-20) that 600 psi was necessary, that it was never possible to build steam as cheaply as 'gas cars', and that cheap gas in the US favoured internal combustion; steamers used more 'gas' per mile than internal combustion. As Rae rightly states though (p.20), boiler water was a consideration; Locomobiles used a gallon a mile.
4. Davison, *Steam Road Vehicles,* 53-4.
5. Foreman-Peck, "American Challenge of the Twenties"
6. McLaughlin "Stanley Steamer"; Rae, *American Automobile Manufacturers,* 41; Arthur "Competing Technologies".
7. Laux and Villalon "Steaming through New England"; Barker, "Introduction"; Liebowitz and Margolis "Network Externality".
8. Siebertz, *Gottlieb Daimler*.
9. Barker 'Introduction'; Diesel et al *From Engines to Autos,* 153.
10. US *Vehicle Industry in Europe,* 358, 360-1.
11. Beasley, *Skulduggery at the Crossroads,* 80-81,124.
12. US *Vehicle Industry in Europe.*
13. Merki, "Birth of Motoring", Tables 1 and 2
14. Beasley, *Skulduggery at the Crossroads,* 80-81,124.
15. *Autocar*, 16-7-1898, pp.459-462.
16. Barjot,"Road Construction Technology", 293.
17. Flink, *America Adopts the Automobile*, 234.
18. Production was estimated at 6132 (US *Census of Manufactures* 1902 p.254) compared with a total of perhaps 8000 in use in the UK.
19. Jenkins, *Motor Cars,* 310.
20. Laux, *European Automobile Industry*, 8.
21. Ibid., 12-14; US *Census of Manufactures 1902* p255; Merki "Birth of Motoring", Table 1)
22. Hasluck, *Practical Treatise*, 780 792.
23. Ibid., 780.
24. Foreman-Peck, "Path Dependence", 218.
25. The 'Locomotives on the Highway' Act (Noble and Mackenzie Junner *Vital to the Nation*), the 1879 legislation on the storage of petroleum (Cummins *Internal Fire*, Ch. 13) and the Lawson patent (see concluding remarks).
26. After his gun-making apprenticeship Daimler enrolled at the School for Advanced Training in the Industrial Arts at Stuttgart in what was to become Germany. He received a travel grant in 1853 to work in an engineering firm in what was then France near Strasbourg (F Rollé and Schwilqué), where there were also theoretical courses. He was awarded a scholarship to study engine design and related subjects, including English, at Stuttgart Polytechnic. Soon after

returning to Strasbourg in 1859 he left for Paris, where the Lenoir gas engine had been patented the previous year. From there Daimler went to visit British engineering companies in Leeds (Smith, Peacock and Tannet), Manchester (Roberts) and Coventry (Whitworths). He met his future colleague, Wilhelm Maybach, in Baden-Württemburg when he was managing director of Bruderhaus Engineering Works (1863-69). Siebertz *Gottlieb Daimler;* Diesel et al *From Engines to Autos.*

27. Rae, *The American Automobile Industry,* 11.

28. Reminiscences of F L Smith of Olds, Rae *American Automobile Manufacturers,* 45.In the US product of 1900 hinged lever steering was still common after the Europeans had instead adopted the steering wheel. H Sturmey 'The Autocar of Today in Europe and America' *Autocar* 17.3.1900 p266.

29. Rae, *American Automobile Manufacturers,* 13.

30. McShane, *Down the Asphalt Path*, 108.

31. Ford, *My Life and Work*, 66; Flink, *America Adopts the Automobile*, 287-8.

32. Broadberry, *Productivity Race.*

33. Flink, *America Adopts the Automobile,* 235-6. The Locomobiles of the Stanley brothers reputedly originated with the inspiration of steam rollers engaged in road making in New England and their hill climbing abilities (H. Dolnar 'American Steam Motocycles' 12.11.98, pp.726-29).

34. Worby Beaumont, *Motor Vehicles,* 458.

35. The efficiency with which heat is converted into mechanical energy for an internal combustion engine today can be as high as 35 to 40% whereas the steam engine has efficiency nearer to 10 to 15%. However, because the internal combustion engine operates at higher temperatures, it must be constructed from stronger materials.

36. Laux, "Diesel Trucks and Buses". Additional evidence that fuel costs determined the national choice of different power source comes from the heavy commercial vehicle sector. British solid fuel steam lorries continued to flourish long after steam cars had disappeared, and the economical diesel engine for road haulage spread faster in Europe during the 1930s than in the US.

37. Williamson et al, *American Petroleum Industry,*172. Jenkins, *Motor Cars*, 812 cites an 1898 Peugeot estimate of running costs which assumes petrol costs 17.3d per gallon. In 1900 'gas' in Geneva cost 9 cents a litre, or roughly 40 cents or 1/8d a gallon (US, *Vehicle Industry in Europe,* 394). Laux, *European Automobile Industry*, 11, states that the general French price was equivalent to 42 cents for an American gallon.

38. Yergin, *Epic Quest for Oil,* 112.

39. Hasluck, *Practical Treatise,* 780.

40. Barker, "Introduction", 16.

41. *Autocar,* 29.10.1898 pp691-3.

42. *Autocar,* 20.1.1900 pp.51-2.

43. *Autocar* 10.9.1898, p.581; *Autocar,* 3.9 1898, pp.564-6.

44. 6000 miles per annum approximately corresponds with the mileages in the preceding car use examples and also with a comparison undertaken by Worby Beaumont, *Motor Vehicles*, ch.36.

45. Hasluck, *Practical Treatise*, 792. Raff and Trajtenberg, "Quality Adjusted Prices" have calculated similar indices for the US market from 1906. They note that consistent information is scarcer before that date

46. The model collapses to a deterministic frontier model when $\sigma^2_v = 0$.
47. The seminal articles are Meeusen and van den Broeck "Efficiency Estimation" and Aigner, Lovell, and Schmidt "Formulation and Estimation".
48. For example, compared with Raff and Trajtenberg's "Quality Adjusted Prices" equations.
49. Marks awarded to each car by the Trial judges was not statistically significant in any of the specifications (not reported in Table 3).

50. Laux, *European Automobile Industry*, 13.
51. And this does not take into account the water consumption of the steamers.
52. The ranking of vehicles in national markets will depend upon national conditions because these determine the mix of vehicles that will be offered for sale (and for competitions). With a 45% tariff and cheaper fuel the US mix would be different from free trade UK and so the rankings may differ. The data identifies the vehicles by maker rather than by model. Occasionally two of the same model appear to be entered but usually when two or more vehicles from the same maker are entered the prices and other specifications differ. Their performances can diverge quite substantially even when the vehicles seem to be the same model, because of different laden weights for instance. One finishing observation (Wilson and Pilcher) was dropped because fuel consumption figure at 8.27 gals. per laden cwt (perhaps six times the maximum likely number) seemed to be a typo.
53. Reliability Trials, Automobile Club of Great Britain, September 1903 (Hasluck, *Practical Treatise*, vol. II 500). Oldsmobile used their achievement in these Trials to advertise in the US the reliability of the 'Curved Dash'. *The Automobile Review and Automobile News* December 15 1903, p.8.
54. Broadberry "Technological Leadership".
55. Dosi, *Technical Change;* Lloyd-Jones and Lewis, "Technological Pathways". Trajectory influences include legislation such as the British 'Locomotives on the Highway Act', repealed in 1896, which is reckoned by some to have retarded the British motor industry (Noble and Mackenzie Junner *Vital to the Nation*), but not by others (Saul "British Motor Industry"). Developments in related sectors include electric battery and motor technology that allowed electric starters for internal combustion motor vehicles from 1911.
56. Wright "American Industrial Success"; Nelson and Wright, "American Technological Leadership". Americans expected to be as forward in the vehicle industry as in other manufacturing sectors when selling abroad. The US Department of State was asked by a large US firm to procure statistical information about the vehicle industry in Europe. The 1900 US Special Consular report on the vehicle industry in Europe was the result.
57. Rae, *American Automobile Manufacturers*, 31.
58. Nineteenth century manufacturing technological change in a prominent interpretation involved the spread of interchangeable parts technology that proved superior to, and replaced, the skilled artisans working with chisel and file (Mokyr, *Lever of Riches*, 137). This form of technical progress requires the increasing ability to measure and machine to higher tolerances. In a static context scarcity of skill in the US may have encouraged interchangeable parts techniques but the contention here is that the advantage of steam is that it required *fewer* interchangeable parts than internal combustion and therefore less skill, not that it needed interchangeable parts replacing handmade components.
59. Davison, *Steam Road Vehicles,* 53.
60. US Census of Manufactures 1902, 256.
61. Ford, *Life and Work*, 25-6.

62. Caunter, *Light Car*, 8-9.
63. Ibid., 1, 8-9.
64. *Autocar* 24.12.1898, pp.824-6; Laux, *European Automobile Industry*, 9.
65. Merki, “Birth of Motoring”.
66. While De Dion dominated internal combustion engines for cars in Europe, the company at the same time made the considered judgement to operate a large steamer department for commercial road vehicles. Heavy road haulage was cheaper and more reliable with steamers in Europe, as traction engines had foreshadowed. Steam was even more suitable for boats. (Davison, *Steam Road Vehicles,* 28-30) For water transport, the power source did not need to vary output as much as for land transport, with hills and stops at junctions and jams, and therefore steam was more competitive on the water by 1895 (with flash boilers).
67. Davison, *Steam Road Vehicles*, 28,50-51.
68. Laux, “Steam Cars”.
69. Rae, “Electrical Vehicle Company”.
70. Noble and Mackenzie Junner, *Vital to the Nation*, 8.
71. Hannah, “Trust , Reputation and Regulation”.
72. Baker, *Marconi Company* .
73. Abelhauser et al, *German Industry and Global Enterprise.*
74. Coleman, *Courtaulds.*
75. Bertram et al, *Solvay.*
76. Broadberry, *Productivity Race*.
77. Magee, “Technological Divergence”.

Table 1 US production of motor vehicles by power source (percentage) 1900-1909

Year	Steam	Electric	Internal Combustion
1900	1681 (40.1)	1575 (37.6)	936 (22.3)
1904	1568 (7.2)	1425 (6.6)	18,699 (86.2)
1909	2374 (1.9)	3826 (3.0)	120,393 (95.1)

Sources: Twelfth, Thirteenth and Fourteenth Censuses of Manufactures in the United States

Table 2 Petrol fuel running costs differentials

	steam mpg	i.c. mpg	Mileage	fuel price	PV
US 1901 Trial	8	16	6000	35c	£117
British 1902 Trial	16	24	6000	35c	£39
British 1902 Trial	16	24	6000	42c	£47

Note: calculated from expression 1.

Table 3 Regressions of Prices of Cars in the UK Automobile Trial 1902

	(i)	(ii)	(iii)	(iv)
Dep. Var. ln price	Frontier	Frontier	OLS	OLS
Fuel gal/cwt	-0.171***		-0.205**	
	(0.0429)		(0.0636)	
H P	0.0356***	0.0236**	0.0437***	0.0376***
	(0.0067)	(0.00737)	(0.00716)	(0.00884)
Cylinders	0.230***	0.193***	0.200***	0.181***
	(0.0349)	(0.0351)	(0.0331)	(0.0357)
Fuel cons. Gal.		-0.0054*		-0.0100**
		(0.0022)		(0.00326)
Laden weight		0.0298***		0.0227*
		(0.00734)		(0.0088)
Gardner-Serpollet			0.395**	0.471**
			(0.136)	(0.173)
Steam			0.0562	0.0228
			(0.11)	(0.0965)
Constant	5.201***	4.738***	5.388***	5.008***
	(0.097)	(0.113)	(0.109)	(0.126)
Ln sig2 *v*	-4.899***	-4.18***		
	(1.16)	(0.53)		
Ln sig2 *u*	-3.072***	-4.133**		
	(0.708)	(1.378)		
N	42	42	42	42
R^2 adj.			0.906	0.909

Notes: s.e. in parentheses, * p<0.05, ** p<0.01, *** p<0.001,
frontier efficiency term half normal distribution.

Table 4 Technological Trajectory of the Internal Combustion Engine 1895-1900 from French Motor Car Races

	Av. speed	Max.speed	No. of finishers	Dist.	Min. speed
June 1895	11.8*	15.25	9++	744 miles	9.0
Sept 1896	14.3	15.9	9	1077 miles	12.8
July 1897	20.4+	23.1	15x	106 miles	16.5
July 1898	21.8	27.0	17	895 miles	15.2
May 1899	25.4	29.9	12	351 miles	22.1
July 1899	26.5	31.9	11	1440 miles	18.8
March 1900	30.8	37.0	16**	125 miles	17.3

Source: calculated from W Worby Beaumont *Motor Vehicles and Motors: Their Design, Construction and Working by Steam, Oil and Electricity*, Constable, London 2 vols 1900,1906 vol 2 p685, vol 1 p388 , pp380-1.

Notes: * Bollee steamer 8.23 ++ 8 int. comb.
+ DeDion Bouton Steamer 24.6 x 14 int comb ** excl Werner bicycle 21.4